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The response of the land biosphere to the ongoing increase in atmospheric CO_2 is not fully understood. To evaluate the approximate upper and lower limits of land sequestration of carbon, we performed simulations using a comprehensive carbon-climate model. In one case the land biosphere is vigorously fertilized by added CO_2 and sequesters carbon throughout the 21st century. In a second case, CO_2 fertilization saturates in year 2000; in this case the land becomes an additional source of CO_2 by 2050. The predicted atmospheric CO_2 concentration at year 2100 differs by 40%between the two cases. Current uncertainties preclude determination of whether the land biosphere will amplify or damp atmospheric CO_2 increases by the end of the century.

Fossil fuel burning and some land-use changes release CO_2 into the atmosphere, where it traps infrared radiation and warms the planet. The response of the land biosphere to this CO_2 increase and climatic change is not fully understood. Higher CO_2

concentrations increase photosynthesis, and ultimately plant growth, when water and nutrients are available. Higher CO_2 also promotes water-use and nitrogen-use efficiency of plants, favoring growth in otherwise limiting situations (1). Biomass and/or soil carbon, and thus terrestrial carbon sequestration, may be expected to increase with higher atmospheric CO_2 levels. However, the effects of photosynthetic CO_2 "fertilization" will saturate at sufficiently high CO_2 levels (1, 2), and higher global temperatures may increase the loss of soil carbon to the atmosphere (1, 3-4).

The physical climatic system and the carbon cycle are a tightly coupled system wherein changes in climate affect exchange of atmospheric CO_2 with the land biosphere and the ocean. Any changes in the function of either the terrestrial biosphere or the ocean – whether anticipated or not– could have significant effects on the fraction of fossil fuel - derived CO_2 that stays in the atmosphere (1). The magnitudes of the feedbacks within the coupled system are poorly constrained. Results from two recent modeling studies, referred to here as Hadley (6) and IPSL (7), led to different conclusions regarding the role of the land biosphere in future global change. Both used coupled climate-carbon ocean-atmosphere general circulation models representing the dynamic response of Earth's climate and carbon system to CO_2 emissions. In the Hadley simulation (6), the land biosphere becomes a net source of CO_2 to the atmosphere by year 2050, whereas in the IPSL simulation (7), it remains a net sink throughout the 21st century. Here, we show that we can produce this change of sign in biospheric response by changing only one unique assumption in a fully coupled three-dimensional model: whether CO_2-fertilization rapidly saturates in terrestrial ecosystems.

Higher atmospheric CO_2 concentration stimulates leaf-photosynthesis and favors stomatal closure allowing more efficient use of available water (8). Models incorporating this dynamic without nutrient constraints to growth tend to be more sensitive to CO_2 fertilization (9, 10). However, in real ecosystems, availability of nitrogen or phosphorous may limit growth, diminishing the sensitivity to added CO_2 (11-13). In a recent study using results from six land biosphere models, it is shown that the estimated future availability of nitrogen is much less (by a factor of two) than is required to support CO_2 fertilization in six CO_2-only simulations and four CO_2-climate simulations (13). There is also experimental evidence that the net production of some ecosystems may decline after a few years of exposure to elevated CO_2 levels and changes like the increased temperature and precipitation predicted by models (14).

To investigate the dynamics of the land biosphere in the coupled climatic system, we developed the INCCA (INtegrated Climate CArbon) model of the dynamics and carbon-balance of the ocean, atmosphere, and land-surface. The physical ocean-atmosphere model is the NCAR/DOE PCTM model (15, 16), which is a version of the NCAR CCM 3.2 model (17) coupled to the LANL POP ocean model (18, 19). The climate model is coupled to a terrestrial biosphere model, the Integrated Biosphere Simulator (version 2) or IBIS2 (20, 21), and an ocean biogeochemistry model. The horizontal resolution of the land and atmospheric model grid is approximately 280 km. The ocean model has a horizontal grid resolution of approximately 70 km with 40 vertical levels.

IBIS2 is a model of land-surface physics, canopy physiology, plant phenology, vegetation dynamics and competition, and carbon cycling for natural vegetation. It simulates surface water, energy, and carbon fluxes on hourly timesteps and integrates them over the year to estimate annual water and carbon balance (20, 21). The annual carbon balance of vegetation is used to predict changes in the leaf area index and biomass for each of 12 plant functional types, which compete for light and water using different ecological strategies. IBIS2 includes soil carbon cycling and heterotrophic respiration (3, 20, 21).

The ocean biogeochemistry model is based on the Ocean Carbon-cycle Model Intercomparison Project (OCMIP) “biotic” protocol (22). This model predicts air-sea CO_2 fluxes, biogenic export of organic matter and calcium carbonate, and distributions of dissolved inorganic carbon, phosphate, oxygen, alkalinity, and dissolved organic matter. In the OCMIP protocol, export of biogenic materials is computed to maintain observed upper ocean nutrient concentrations. However, because our simulations involve changes in ocean circulation, we cannot make the assumption that surface nutrient concentrations remain stationary. Therefore, we replaced the OCMIP export formulation with a formulation based on that of Maier-Reimer (23, 24)

We integrated the fully coupled model to quasi-equilibrium to form an 1870 “pre-industrial” initial condition (25). We performed three model cases starting from this pre-industrial initial state.

The "control” case has no CO_2 emissions and thus no change in radiative forcing for the period 1870-2100. Model drift evaluated for the period 1900-2100 is a cooling of 0.35 K in mean surface temperature, and a 3.14 ppmv increase in atmospheric CO_2 concentration. Both are residuals from a slight imbalance in the initial state. Since the control drifts are minimal, they are not subtracted from the other simulations in our analysis.

The "fertilization" case has CO_2 emissions specified at historical levels for 1870-2000 (26) and that follow the IPCC scenario SRES A2 from 2000-2100 (1). Non-CO_2 greenhouse gas concentrations are specified at historical levels for 1870-2000 and SRES A2 levels from 2000-2100 (1). Land use emissions are reconstructions (27) for the historical period and from the SRES A2 scenario thereafter. There is no change in the static “background” aerosol forcing used in the control case. In this scenario, total emissions reach 29 Gigatons carbon (GtC) per year in year 2100 from present day values of 8 GtC per year.

The “saturation” case is identical to the fertilization case except the CO_2 fertilization is assumed to saturate at the year 2000 concentration (366 ppmv); the terrestrial biosphere model is forced not with the predicted CO_2 after year 2000, but with a constant CO_2 concentration of 366 ppmv.

We believe that these cases will bracket the reasonable range of nitrogen and/or other limitation on carbon sequestration in the terrestrial biosphere. Since IBIS2 is one of the most responsive models to CO_2 fertilization (10), the fertilization case will probably approximate an upper limit to the land uptake of carbon assuming unlimited nitrogen/nutrient availability. Capping all fertilization at its year 2000 value in the saturation case will approximate a strongly nitrogen/nutrient limited system.

Figure 1a shows that assumptions regarding CO_2-saturation of the land biosphere greatly affect the atmospheric concentration of CO_2. Year 2100 atmospheric CO_2 concentrations are 336 ppmv higher in the saturation case than in the fertilization case. In the SRES A2 scenario, 1790 GtC is emitted to the atmosphere over the 21st century;

atmospheric CO_2 content increases by 776 GtC (366 ppmv) and 1489 GtC (702 ppmv) in our fertilization and saturation cases, respectively.

The global climate carbon feedback factor is a useful system metric defined as the ratio of CO_2 change when climate is changing to the CO_2 change when climate is constant (28). We performed an additional constant-climate simulation with full emissions to determine this factor and obtain a value of 1.13 for our fertilization case. The feedback factors for similar fertilization simulations are 1.19 for IPSL (7) and 1.68 for Hadley (6). Therefore, our model shows the weakest positive feedback between climate and the carbon cycle of the current published results for fertilization cases. Note, however, that our feedback factor increases to 2.05 in our saturation case. This is an indication of the uncertainty in quantifying the climate-carbon cycle feedback arising from a single model assumption.

The temperature difference at year 2100 between the saturation and fertilization cases is only 0.7 K (Fig. 1b), but it should be noted that the climatic system has large thermal inertia due to the large heat capacity of the oceans. If the simulations were run to equilibrium with the year 2100 CO_2 values, the temperature difference would be approximately 1.1 C (estimated from the PCTM equilibrium climate sensitivity of 2.1 K per doubling of CO_2)

Simulation results (Fig. 2a) show that assumptions regarding the saturation of CO_2-fertilization can affect the sign of atmosphere/land-biosphere CO_2 flux by century's end. In the case of the land biosphere, there is competition between direct CO_2 effects and temperature effects. Direct CO_2 effects can be expected to lead to increased terrestrial carbon uptake, but temperature effects can lead to increased heterotrophic respiration and loss of soil carbon (6, 7, 10, 29), at least until a possible acclimation of soil microbiology to the higher temperatures (30, 31). In the saturation case, by year 2100 the land-biosphere has become a net source of CO_2 to the atmosphere, as temperature effects dominate CO_2-fertilization effects. In the fertilization case, CO_2-fertilization effects dominate temperature effects, resulting in continued net biospheric growth.

In contrast to Hadley (6), but in agreement with IPSL (7), our land carbon cycle does not become a net source of carbon to the atmosphere in the fertilization case. A loss of vegetation biomass does not occur in either of our simulations (but soil carbon does decline by year 2100 in our saturation case).

Between year 2000 and year 2100, ocean/atmosphere carbon fluxes show significant differences between the fertilization and saturation cases (Fig. 2b). Ocean carbon storage increases by 269 and 357 GtC in the two cases (Fig 2c). Ocean uptake is greater in the saturation case because atmospheric CO_2 concentrations are greater, driving an increased flux of CO_2 from the atmosphere to the ocean (32, 33). However, surface warming tends to reduce the dissolution of atmospheric CO_2 in the ocean. Surface warming also tends to cause increased thermal stratification, which inhibits downward transport of anthropogenic carbon. However, with increased stratification, the residence time of nutrients in the euphotic zone increases, allowing a greater fraction of nutrients to be exported from the surface layers as particulate organic carbon. This effect tends to counteract some of the direct physical effects of increased stratification (32, 33). The direct CO_2 effects appear to be much larger than the temperature effects; hence CO_2 added to the atmosphere drives an increased flux into the ocean in the saturation case.

Cumulative emissions since 1870 reach 2200 GtC by year 2100 (Fig. 2c). In the fertilization case, the land biosphere and the oceans sequester 919 GtC (42%) and 346 GtC (15.5%) of the total emissions respectively. In the saturation case, the corresponding amounts are 104 GtC (5%) and 435 GtC (19.5%). Therefore, land sequestration of carbon due to the degree of CO_2 fertilization varies from 5% to 42% of the total emissions in our model. The remaining amounts 935 GtC (42.5%) and 1661 GtC (75.5%) stay in the atmosphere in the fertilization and saturation cases respectively.

The C:N ratio of soil in our model is approximately 11. Assuming a constant C:N ratio of 200 for live biomass (13), the total land ecosystem nitrogen increases by 20 Gt between year 2000 and 2100 in the fertilization case. This is much larger than estimates which show that only 6 Gt of additional nitrogen could accumulate in the terrestrial biosphere by 2100 (13). In contrast, in the saturation case nitrogen in the terrestrial biosphere declines by 8 Gt during the same period. A large implied accumulation of nitrogen in one case and its release in the other suggest that our simulations bracket a plausible range of nitrogen/nutrient limitations on carbon sequestration in the terrestrial biosphere.

The geography of simulated carbon uptake in the fertilization case over the period 1870-2100 (Fig. 3) shows that anthropogenic carbon is stored on land primarily in areas of high vegetation productivity (Amazonia, central Africa, south and southeast Asia, and the boreal forests). Currents and circulation make storage somewhat more uniform for the ocean, but it is higher in the North Atlantic and Mid-Southern Oceans, which reflects proximity to regions of net CO_2 uptake (34, 35).

Even without the nutrient limitations, the enhanced physiological effects of CO_2 on photosynthesis and water use efficiency will level off at high CO_2 concentration (1, 2, 36, 37). If saturation of CO_2 fertilization will occur before saturation of greenhouse infrared absorption, the carbon loss due to warming may be the dominant long-term impact on the land biosphere; the ability of land to sequester future emissions will be hampered. The climate model used here has an equilibrium climate sensitivity to increased CO_2 (2.1 K per doubling) that is at the lower end of the range of the general model population (1). A more sensitive climate model would increase the amount of warming, increasing heterotrophic respiratory carbon fluxes from soils even more. Hence, high climate sensitivity is more likely to amplify carbon losses from the land biosphere; a low climate-sensitivity is more likely to allow the land biosphere to damp the climate effects of CO_2 emissions, with carbon uptake by the biosphere dominated by CO_2 fertilization.

The results of this fully coupled climate-carbon model show that the amount of anthropogenic CO_2 in the atmosphere at the end of this century will probably be sensitive to carbon-cycle processes about which we are uncertain at present. We are in the infancy of developing mechanistic understanding of the controls on land-biosphere carbon fluxes and representing that understanding in global gridded models. Right now, whether the land-biosphere damps or amplifies global warming seems to depend on highly uncertain assumptions regarding the response of the biosphere to increased CO_2 and a changed climate. These uncertainties could perhaps be narrowed with investigation of carbon dynamics across a broad range of ecosystems and climatic regimes, often including manipulation experiments, and redoubled efforts to represent those dynamics numerically. Without this research, we cannot predict if the land biosphere will help or hinder our efforts to stabilize climate.

References and Notes

1. J.T. Houghton *et al.*, Eds., *Climate Change 2001*, *The Scientific Basis* (Cambridge Univ. Press, Cambridge, 2001.)
2. Farquhar, G.D., S.V. von Caemmerer, and J.A. Berry, *Planta*, **149**, 78 (1980).
3. Lloyd, J., and J.A. Taylor, *Functional Ecology*, **8**, 315 (1994).
4. Giardina, C.P., and M.G. Ryan, *Nature*, **404**, 858 (2000).
5. J.M. Melillo, et al., *Science*, **298**, 2173 (2002).
6. P. M. Cox, R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell, *Nature*, **408**, 184 (2000).
7. P. Friedlingstein et al., *Geophys. Res. Lett.*, **28**, 1543 (2001).
8. Owensby, C.E., J. M. Ham, A. K. Knapp, L. M. Auen, *Global Change Biology*, **5**, 597 (1999).
9. D. W. Kicklighter et al., *Tellus*, **51B**, 343 (1999).
10. W. Cramer et al., *Global Change Biology*, **7**, 357 (2001).
11. D. S. Schimel, *Nature*, **393**, 208 (1998).
12. K. J. Nadelhoffer et al., *Nature*, **398**, 145-148 (1999).
13. B. A. Hungate, J. S. Dukes, M. R. Shaw, Y. Luo, and C. B. Field, *Science*, **302**, 1512 (2003).
14. M. R. Shaw, E. S. Zavaleta, N. R. Chiarillo, E. E. Cleland, H. A. Mooney, C. B. Field, *Science*, **298**, 1987 (2002).

15. W. M. Washington et al., *Climate Dynamics*, **16**, 755 (2000).

16. G. A Meehl, et al., *J. Climate* (in press)

17. J. T. Kiehl et al., Description of the NCAR Community climate Model (CCM3). *NCAR Tech. Note*. NCAR/TN-420+STR, (1996).

18. J. K. Dukowicz, R. D. Smith, *J. Geophys. Res*., **99**, 7991 (1994).

19. M. E. Maltrud, R. D. Smith, A. J. Semtner, A. J. Malone, *J. Geophys. Res*., **103**, 30825 (1998).

20. J. A. Foley et al., *Global Biogeochem. Cycles*, **10**, 603 (1996).

21. C. J. Kucharik et al., *Global Biogeochem. Cycles* **14** (3), 795 (2000).

22. R. G. Najjar, J.C. Orr, Biotic How-To, Revision 1.7, Ocean Carbon-cycle Model Intercomparison Project (OCMIP) (1999), http://www.ipsl.jussieu.fr/OCMIP/phase2/simulations/Biotic/HOWTO-Biotic.html

23. E. Maier-Reimer, *Global Biogeochemical Cycles*, **7(3)**, 645 (1993).

24. Export formulation (23) is $J_{PROD} = (1/\tau) \bullet g(PAR) \bullet Q_{10}^{(\Delta T/10)} \bullet P^2 / (P_{1/2} + P)$, where J_{PROD} is phosphate uptake rate for production of both exported particulate organic matter and dissolved organic matter; τ is the time constant for phosphate removal from the surface layer at 25^0C in the case of sufficient nutrients and light (here taken to be 60 days); g(PAR) is light sensitivity of growth (38); temperature dependence on growth rate was modeled using Q_{10}=2 (39). P is the phosphate concentration; we used a half saturation value for phosphate, $P_{1/2}$, of 2e-5 mol/m^3 (23).

25. When IBIS2 was coupled to the PCTM, precipitation biases typical of current climate models caused vegetation errors that, in turn, amplified precipitation biases

in regions where surface-atmosphere moisture recycling is known to be important. This erroneous feedback resulted in unacceptable vegetation in some areas, particularly parts of the Amazon. To remedy this, a precipitation correction scheme was implemented. At every surface grid point, and every time step, the simulated precipitation field is multiplied by a constant that is a function of position, but otherwise static and identical across all runs. The constant “correction field” acts to move the model’s simulated present-day annual mean precipitation towards an observed climatology. However, we maintain the model’s global conservation of water and energy. In effect the procedure spatially redistributes the model’s precipitation at each time step. This correction has minimal impact on the model’s daily and seasonal precipitation characteristics and allows for global hydrologic changes.

26. G. Marland, T. Boden, R. Andres, Global, regional, and national annual CO_2 emissions from fossil-fuel burning, cement production and gas flaring: 1751-1999, *CDIAC NDP-030*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Tennessee.
27. R. Houghton, *Tellus*, **55B**, 378 (2003).
28. P. Friedlingstein, J.-L. Dufresne, P. M. Cox, P. Rayner, *Tellus*, **55B**, 692 (2003).
29. F. Joos, et al., *Global Biogeochemical Cycles*, **15**, 891 (2001).
30. Kirschbaum, M.U.F., *Biogeochemistry*, **48**, 21 (2000).
31. Tjoelker, M.G., *et al.*, *Global Change Biology*, **7**, 223 (2001).
32. J. L. Sarmiento, C. Le Quere, *Science*, **274**, 1346 (1996).
33. J. L. Sarmiento, M. C. Hughes, R. J. Stouffer, S. Manabe, *Nature*, **393**, 245 (1998).

34. M. E. Wickett, K. Caldeira, P. B. Duffy, *J. Geophys. Res. (Oceans)*, **108**, art. no. 3189 (2003).

35. K. Caldeira, P. B. Duffy, *Science*, **287**, 620 (2000).

36. A. W. King, W. M. Post, S. D. Wullschleger, *Climatic Change*, **35**, 199 (1997).

37. M. Cao, F. I. Woodward, *Nature*, **393**, 249 (1998).

38. R. C. Tian et al., *Deep-Sea Research*, **47**, 637 (2000).

39. D. Wolf-Gladrow, U. Riebesell, *Mar. Chem.*, **59**, 17 (1997).

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Figure Captions

Figure 1. (a) Simulated atmospheric CO_2 from 1870 to 2100. Unforced control (black), fertilization case (green), and saturation case (red). Black dots are observed CO_2 concentrations. If CO_2 fertilization saturates early, the land-biosphere becomes a net source of CO_2 to the atmosphere, adding to anthropogenic CO_2 emissions. (b) Simulated global mean surface temperature for the same cases as (a).

Figure 2. (a) Global flux of carbon from land to atmosphere. Unforced control (black), fertilization case (green), and saturation case (red). In the saturation case the land becomes a net source of carbon by year 2050. (b) The same as (a) but for carbon flux from ocean to atmosphere. (c) Global carbon change from the 1870 "pre-industrial" starting point. Total earth system (black), land (solid), and ocean (dashed). Fertilization case (green), and saturation case (red)

Figure 3. The simulated geography of carbon stored in the earth system over the period from 1870 to 2100 (column integrated carbon in kg C / m^2) in the fertilization case. Anthropogenic carbon is stored primarily in areas of high vegetation productivity and/or cooler climates over land. Owing to currents, storage is somewhat more uniform for the oceans, but higher in the North Atlantic and Mid-Southern oceans which reflects proximity to regions of net CO_2 uptake.

Figure 1

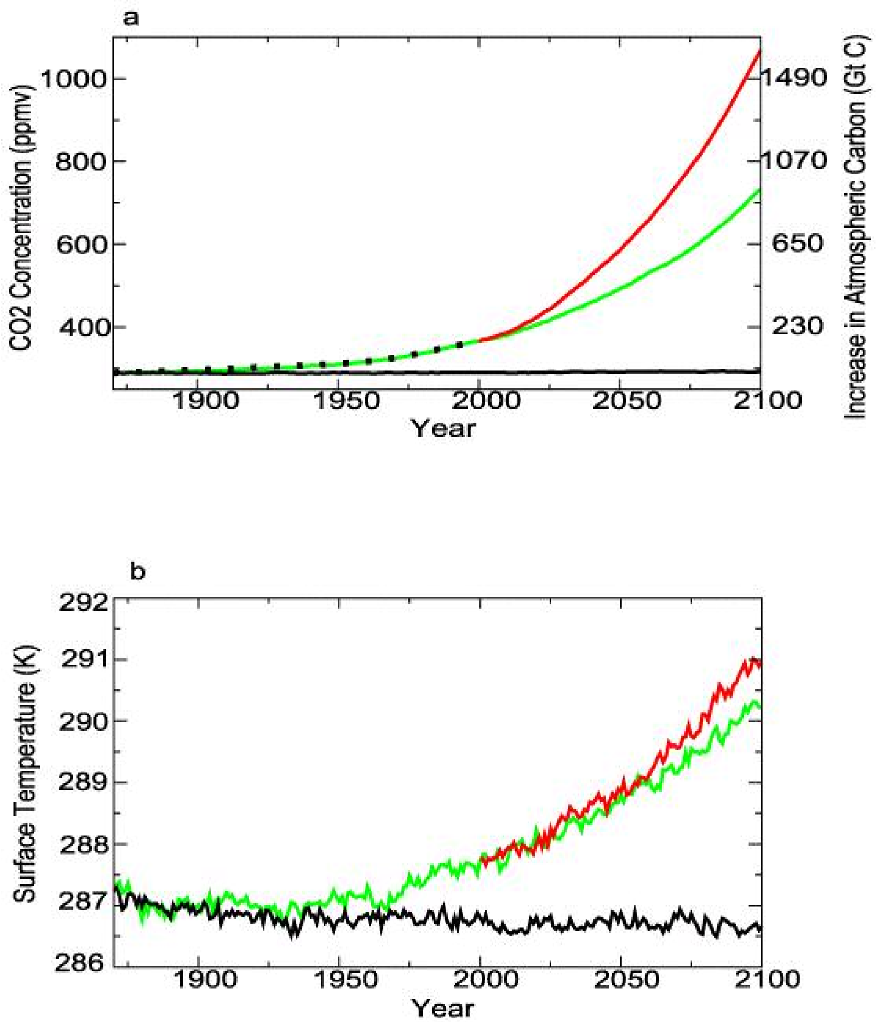
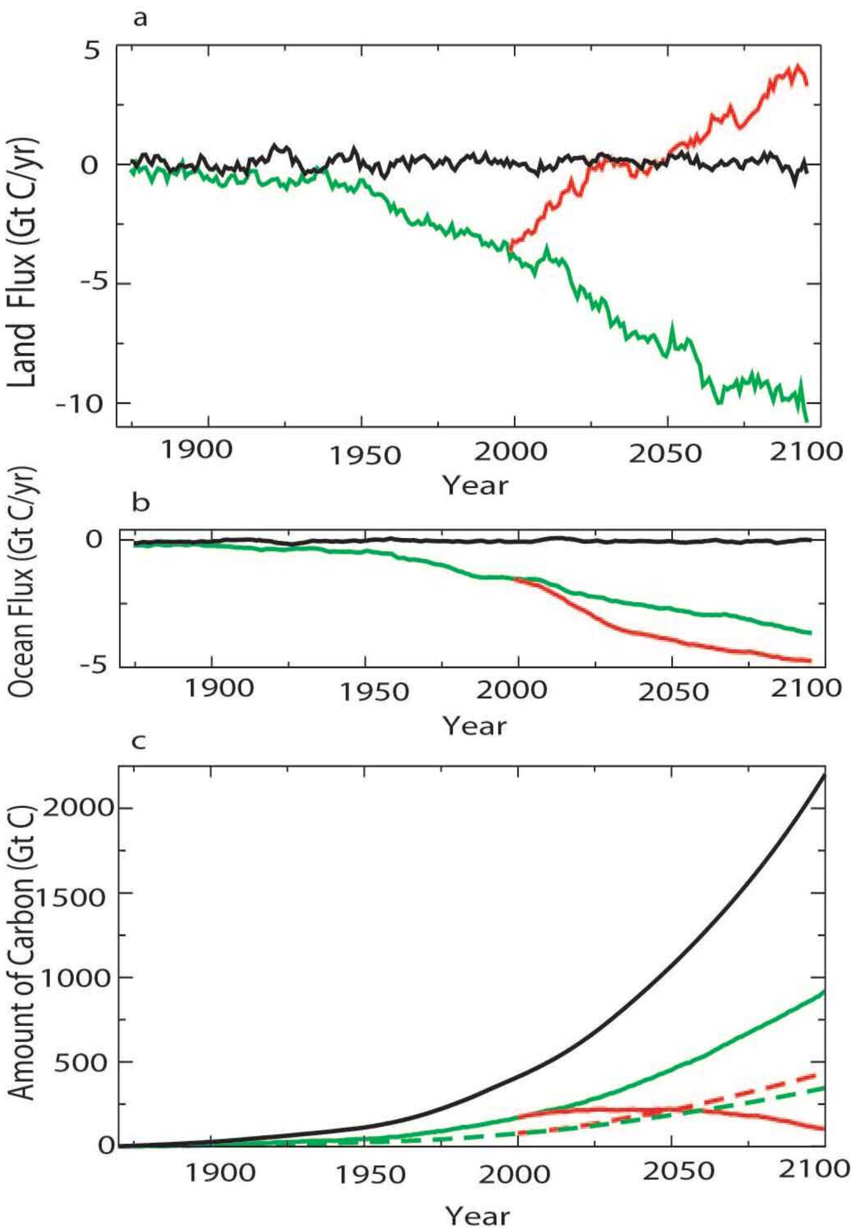

a
CO2 Concentration (ppmv)
1000
800
600
400
1490
1070
650
230
Increase in Atmospheric Carbon (Gt C)
1900
1950
2000
2050
2100
Year
b
Surface Temperature (K)
292
291
290
289
288
287
286
1900
1950
2000
2050
2100
Year

Figure 2



a
Land Flux (Gt C/yr)
5
0
-5
-10
1900
1950
2000
2050
2100
Year
b
Ocean Flux (Gt C/yr)
0
-5
1900
1950
2000
2050
2100
Year
c
Amount of Carbon (Gt C)
2000
1500
1000
500
0
1900
1950
2000
2050
2100
Year

Figure 3